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RESEARCH MEMORANDUM

INFLUENCE OF BORIC OXIDE DEPOSITION ON TURBOJET-

ENGINE OPERATION

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INFLUENCE OF BORIC OXIDE DEPOSITION ON TURBOJET ENGINE OPERATION

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SUMMARY

In an effort to provide a better understanding of the effect of oxide-depositing fuels on engine starting, operation, and performance, a modified production turbojet engine was operated using a trimethyl borate azeotrope as a fuel. Trimethyl borate, a comparatively low-heating-value fuel that forms boric oxide during combustion, was used as a substitute for the more expensive and less available boron hydride fuels currently under consideration.

Operation with trimethyl borate for 100 minutes produced a 2-percent deterioration in engine speed and only a 1-percent increase in combustor total-pressure loss with the best engine configuration investigated. The deposits had no measurable effect on the turbine efficiency. Following the operation with trimethyl borate fuel, the engine was operated with a hydrocarbon fuel (JP-4) to dissipate the boric oxide deposits. After 50 minutes of operation with JP-4 fuel, the deposits were substantially removed and the engine approached normal operation.

INTRODUCTION

The need for lower specific fuel consumption in modern high-speed aircraft to provide increased flight range or endurance is generally recognized. Consideration of the factors that influence the flight range will provide an insight into possible sources of improvement. The flight range as defined by the Breguet equation (ref. 1),

$$R \approx h_f \eta_c \, \frac{L}{D} \, \ln\left(\frac{W_i}{W_f}\right)$$

is directly proportional to the chemical heating value of the fuel h_f and to the combustion efficiency η_c. Because of the high level of combustion efficiency usually obtained in current turbojet engines, improvement of range by increases in combustion efficiency will be small. A detailed discussion of the possible improvements in over-all lift-drag and gross weight relations of current aircraft is outside the scope of

this report, but there is little likelihood of very large changes in
the immediate future. Large increases in range appear possible, however,
by the use of fuels having an increased heating value with approximately
the same density as the currently used hydrocarbon fuels.

One group of fuels currently under study, the boron hydrides,
possess 50 percent more chemical heat per pound than the conventional
hydrocarbon fuels. However, several characteristics of these fuels tend
to impede immediate exploitation of this significant advantage in per-
formance. Some of the boron hydrides are dangerously toxic; in general,
they have only moderate chemical stability; they are currently expensive
to manufacture and they form viscid products of combustion.

The formation of boric oxide B_2O_3 during combustion and its sub-
sequent deposition on the surfaces of the engine components presents a
source of performance deterioration. The present investigation was
accordingly conducted to study the influence of boric oxide deposition
on the operation and performance of the combustor, the turbine, and
the over-all engine. A substitute fuel of much lower cost than the
boron hydrides, an azeotropic mixture of trimethyl borate and methyl
alcohol, was used. This substitute fuel has a heating value of three-
eighths and an oxide deposition rate of one-third of that of pentaborane,
a potentially useful boron hydride fuel. Therefore, the results of this
investigation should be used only as an indication of the effect of
boron-oxide-depositing fuels on the engine operation and performance.

Trimethyl borate was supplied to a production-model turbojet engine
to which only minor modifications had been made. The investigation
was conducted with the engine operating at sea-level static conditions.
Several runs were made with a total operating time of approximately
$10\frac{1}{2}$ hours. The influence of the deposits on the combustor pressure loss,
the turbine efficiency, and the over-all engine operation and performance
is presented. Photographs of the deposits formed in the various com-
ponents of the engine are included. Dissipation of the boric oxide
deposits was accomplished by operation with JP-4 fuel. These results
are also presented.

APPARATUS

Engine and installation. - The turbojet engine used in this investi-
gation was a standard production model with a nominal thrust rating of
5920 pounds at a rotational speed of 7950 rpm and a turbine-discharge
gas temperature of 1275° F. A schematic diagram of the engine is shown
in figure 1. The following modifications were made to the engine for
operation with the trimethyl borate fuel:

Configuration	Modifications to standard engine		
	Turbine clearance	Combustor retainer-ring flow area	Fuel nozzles
A	Increased[a]	Increased[b] $3\frac{1}{2}$ times standard area	Large slot enlarged
B	Increased[a]	Blocked	Large slot enlarged
C	Standard	Blocked	Large slot enlarged

[a]See fig. 2(a).
[b]See fig. 2(b).

A single combustor of the engine was equipped with a thimbled liner to explore the effect on the deposition.

The engine was installed in a static, sea-level test cell that drew in atmospheric air and exhausted into a sound-muffling chamber at approximately atmospheric pressure. The inlet-air temperature was controlled by the use of a preheater.

Fuel specifications. - The fuel supplied to the engine was an azeotropic mixture of 70 percent trimethyl borate $B(COH_3)_3$ and 30 percent methyl alcohol CH_3OH by weight. This fuel produces boric oxide at a rate of 33 pounds per million Btu heat release. Although four boric oxide compounds are possible from the oxidiation of boron compounds depending on the completeness of combustion, B_2O_3 is the most prevalent. It occurs in both crystalline and vitreous form; the crystalline form solidifies at 842° F, while the vitreous form begins to solidify at approximately 1070° F. The fuel properties are as follows:

Specific gravity, 60°/60° F 0.894
Viscosity at 100° F, centistokes 0.424
Lower heating value, Btu/lb 8060
Formula weight 138.87

The fuel used in this investigation was supplied by the Bureau of Aeronautics, Department of the Navy, as part of Project Zip.

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Instrumentation. - The number and location of the total- and static-
pressure and temperature instrumentation used in this investigation are
tabulated in figure 1. Pressure instrumentation used downstream of the
combustor outlet was of the air-purging type to exclude collection of
boric oxide and subsequent blockage. A sketch of a typical purging-type
pressure probe is shown in figure 3.

PROCEDURE

All operation of the engine with trimethyl borate fuel was at sea-
level static conditions. The engine inlet-air temperature was main-
tained at 100° F by mixing the intake air with air heated by a preheater.
Constant engine fuel flow and exhaust-nozzle area were maintained
throughout the tests, and the engine speed was permitted to vary with
boric oxide deposition on the engine components so as to maintain a
fixed tail-pipe temperature. The engine was limited to a maximum
rotational speed of 7750 rpm and a turbine-outlet temperature of 1240° F
to ensure extended turbine life during the investigation. For this
investigation, these operating conditions will be referred to as rated
conditions.

Five runs of approximately 2 hours each were made for a total
operating time of $10\frac{1}{2}$ hours with trimethyl borate. The random deposition
and erosion of the boric oxide encountered throughout the engine precluded
exact reproduction of each test run, but reasonable consistency was
achieved with only minor variations when a large segment of deposit was
broken off. Good agreement was achieved between two runs involving like
conditions.

Following a period of operation with trimethyl borate for 130 min-
utes, the engine was operated with JP-4 fuel to observe the rate of
dissipation of the boric oxide deposits.

RESULTS AND DISCUSSION

The use of a fuel that produces viscid products of combustion in a
turbojet engine that was designed to operate with hydrocarbon fuel
presents a series of unique problems. These problems include a deter-
mination of the deposition characteristics of the products of combustion,
the influence of these deposits on engine starting, operation, and
performance, and finally how the deposits might be dissipated.

Boric oxide deposition. - The engine was successfully started with
trimethyl borate fuel, and only moderate immediate deposits were formed
on the relatively cold metal components during starting. The deposits

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in a typical combustion chamber are shown in figure 4 following the engine start and approximately 7 minutes of operation.

After 2 hours of operation with trimethyl borate fuel, the boric oxide deposits reached the state shown in figure 5. Figure 5(a) shows the deposits in the combustion-chamber liner that was equipped with thimbles that protruded into the combustion chamber to provide additional turbulence in the combustion zone. The liner of figure 5(b) was without thimbles. Both types of combustor liner are in use in current turbojet engines. In general, these deposits were vitreous with only minor crystalline formations. Figure 5(c) compares a clean liner with the plugging obtained longitudinally in a combustion-chamber liner after 2 hours of operation with trimethyl borate. The oxide deposits in the tail pipe following the same period of operation are shown in figure 5(d). Although some crystalline deposits are visible, the majority of the oxide in the tail pipe is in a vitreous form and appears to have been plastic while still molten.

Engine operation and performance. - The engine fuel flow and exhaust-nozzle area were maintained constant and the engine speed was permitted to decrease so as to maintain a tail-pipe temperature of 1700° R. A maximum engine speed decrease of 2 percent was measured using configuration A as is shown in figure 6. The decrease in engine speed resulted from the increased combustor pressure drop and the burning of some of the fuel downstream of the turbine as may be seen from figure 7. Operation was for 100 minutes with trimethyl borate fuel. The irregular changes in engine speed that occurred at 45 and 85 minutes are believed to have resulted from the dislodgment of sizeable quantities of the accumulated deposits of the combustor.

It may be seen in figure 7(a) that the turbine-discharge gas temperature decreased with time (increasing deposition) while the gas temperature measured downstream (at the exhaust-nozzle inlet) remained constant.

The effect of the boric oxide deposits that accumulated in the combustion chambers (shown in photographs of fig. 5) was to increase the total-pressure loss in the combustor. Following 100 minutes of operation with the trimethyl borate fuel, the combustor total-pressure ratio (outlet to inlet) decreased from 95.6 to 94.6 percent (fig. 7(b)).

The accumulated deposits in the combustor could have an effect on the gas-flow conditions entering the turbine nozzle diaphragm that would be reflected by changes in the temperature and total-pressure gradients

at the turbine. Figure 8 shows the variation of the turbine-inlet gas-
temperature profile at several time intervals during operation with
trimethyl borate. Radial profiles are shown for positions at the turbine
inlet both behind a combustor and between two combustors. In general,
a somewhat steeper temperature gradient from the inner portion of the
annulus to the outer wall was experienced with prolonged use of the
trimethyl borate. The change in turbine-inlet total-pressure profile
is shown in figure 9. Both the circumferential pressure distribution
(fig. 9(a)) and the radial pressure profile (fig. 9(b)) were slightly
altered because of the accumulated boric oxide deposits in the combustor.

Although the combustor deposits altered the temperature and pressure
distributions entering the turbine nozzle diaphragm, these relatively
small changes were insufficient to produce a measurable change in the
performance of the turbine. The turbine efficiency (fig. 10) remained
constant throughout the investigation even with prolonged use of the
trimethyl borate fuel.

Effect of turbine-inlet temperature. - Temperature is known to
influence both the type of boric oxide formed and the rate of deposition
and erosion. To investigate the effect of temperature on the influence
of boric oxide deposition on the engine performance, the engine was
operated at tail-pipe temperatures of 1460° and 1650° R with correspond-
ing turbine-inlet temperatures of approximately 1880° and 2050° R.
Configuration B was used in this phase of the investigation and differed
from that used to obtain the data of figure 6 in that the combustor-
outlet retainer ring was replaced by a blank that prevented cooling air
from reaching the turbine nozzle diaphragm. It was expected that the
higher surface temperatures of the nozzle diaphragm would facilitate
the oxide erosion. The variation of the turbine-inlet temperature was
made by varying the exhaust-nozzle area and the engine fuel-flow rate.

With a turbine-inlet gas temperature of 1880° R, the oxide deposits
caused a 2.8-percent reduction in engine speed. Increasing the turbine-
inlet temperature from 1880° to 2050° R caused an engine speed deteriora-
tion of approximately 7.3 percent for a similar quantity of fuel con-
sumption. The comparison of engine speed deterioration is presented in
figure 11 as a function of the accumulated fuel consumption because
the oxide formation is a direct function of the fuel-consumption rate.
The tendency to increase the oxide deposition and consequently cause a
further speed deterioration with increased turbine-inlet temperature is
contrary to expectation. It was anticipated that the erosion would
increase with the reduced viscosity of the deposits at higher tempera-
tures. The increased oxide-deposition trend, however, has been substanti-
ated with unpublished data obtained on a single combustor rig. It is
believed that this incongruity can be explained by the fact that the

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increased fuel-flow rate required for the higher turbine-inlet temperature may produce impingement of the fuel on the combustor walls and thus promote local deposition. This condition has not been conclusively determined as yet.

The irregularity of the data shown in figure 11 for 2050° R turbine-inlet temperature for fuel consumption between 8000 and 10,000 pounds is again believed due to a sudden change in the deposits such as would occur with the dislodgment of large pieces.

It should again be noted that for these data the cooling air to the nozzle diaphragm was blocked and that they are therefore not comparable to the data of figure 6.

Dissipation of boric oxide deposits. - The engine was operated for 130 minutes with trimethyl borate fuel, and the usual boric oxide deposition was encountered. For this phase of the investigation configuration C was used. Configuration C was similar to configuration B except that the turbine clearance was not modified. The effect of the deposition on engine speed was similar to that obtained with configuration B and shown in figure 11. The speed decrease to 92.7 percent shown in figure 11 for an accumulated fuel consumption of 19,400 pounds corresponds to the 92.0-percent engine speed shown in figure 12 after 100 minutes of operation. The 7- to 8-percent decrease in engine speed obtained with configurations B and C is in contrast to the 2-percent decrease encountered with configuration A where the nozzle diaphragm was maintained at a cooler temperature.

Subsequent to the operation with trimethyl borate, the engine was operated with hydrocarbon fuel, JP-4. After about 50 minutes of operation with JP-4, the engine speed approached normal operation, as is shown in figure 12, indicating substantial removal of the deposits. Visual inspection showed that the deposits throughout the engine were dissipated by the JP-4 operation. Figure 13(a) shows the deposits in a typical combustor following operation with JP-4 fuel, and figure 13(b) shows the relatively minor deposits remaining in the engine tail pipe.

CONCLUSIONS

This investigation has demonstrated that it is possible to start a turbojet engine with a boric-oxide-depositing fuel without immediate serious deposition on the relatively cold engine components. Following 100 minutes of operation with the trimethyl borate fuel and consequent deposition of boric oxide, a 2-percent reduction in engine speed and a 1-percent increase in combustor total-pressure loss were measured with the best engine configuration investigated. The deposits had no measurable effect on the turbine efficiency.

The deposition accompanying the consumption of approximately 20,000 pounds of trimethyl borate during operation of the engine at a turbine-inlet gas temperature of 1880° R caused a 2.8-percent reduction in engine speed. Similar operation at a turbine-inlet gas temperature of 2050° R resulted in a 7.3-percent engine speed decrease.

Operation with JP-4 fuel following boric oxide accumulation has been shown to be an effective method of dissipating the deposits. After 50 minutes operation with JP-4, the deposits were substantially removed and the engine speed approached normal operation.

Lewis Flight Propulsion Laboratory
    National Advisory Committee for Aeronautics
        Cleveland, Ohio, February 10, 1955

APPENDIX - SYMBOLS

The following symbols are used in this report:

h_f heating value of fuel, Btu/lb

L/D   over-all lift divided by drag for airplane

P   total pressure, lb/sq ft abs

T   total temperature, $^\circ$R

W   airplane gross weight

η efficiency

Subscripts:

c   combustion

f   final

i   initial

t   turbine

3   combustor inlet

4   turbine inlet

REFERENCE

1. Schamberg, R.: Effects of Flight Speed and Propulsive System on
   Aircraft Range. Rep. R-114, The Rand Corp., Aug. 13, 1948. (USAF
   Proj. MX-791, Proj. Rand.)

Station 1

CD-4201
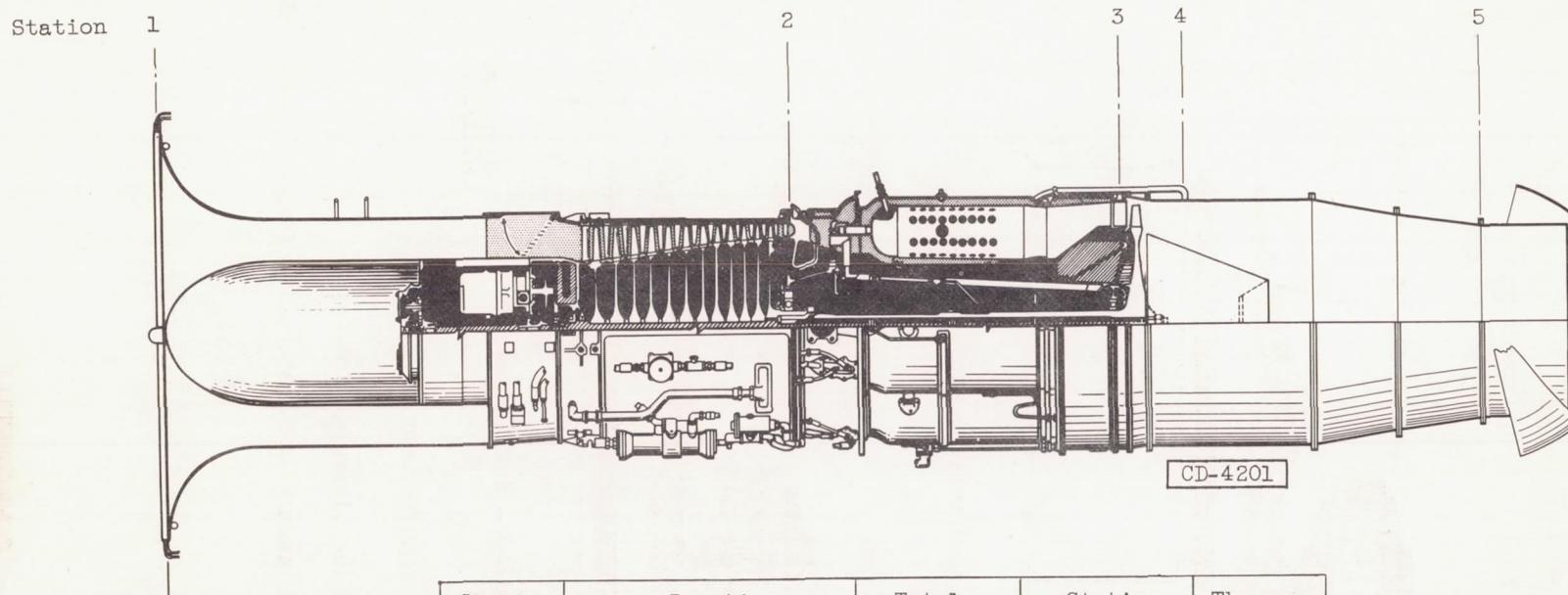
Station	Location	Total-pressure probes	Static-pressure probes	Thermo-couples
0	Inlet air measuring station	9	7	4
1	Engine inlet	-	-	20
2	Compressor outlet	10	4	10
3	Turbine inlet	12	-	30
4	Turbine outlet	7	-	20
5	Exhaust-nozzle inlet	12	-	14

Figure 1. - Schematic diagram of turbojet engine showing location of pressure and temperature instrumentation used throughout engine.

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Standard turbine shroud

Modified turbine shroud
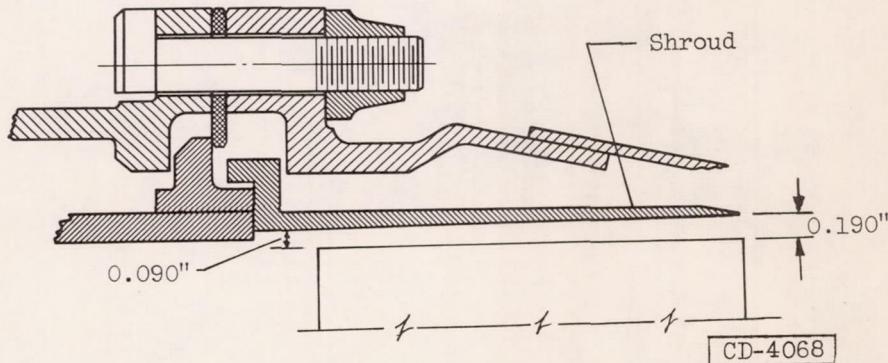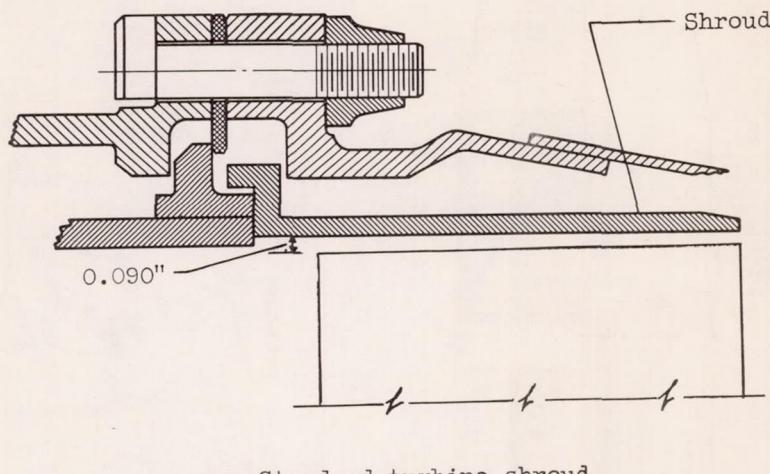
(a) Turbine-clearance increase.

Figure 2. - Modifications to standard turbojet-engine components for operation with trimethyl borate fuel.
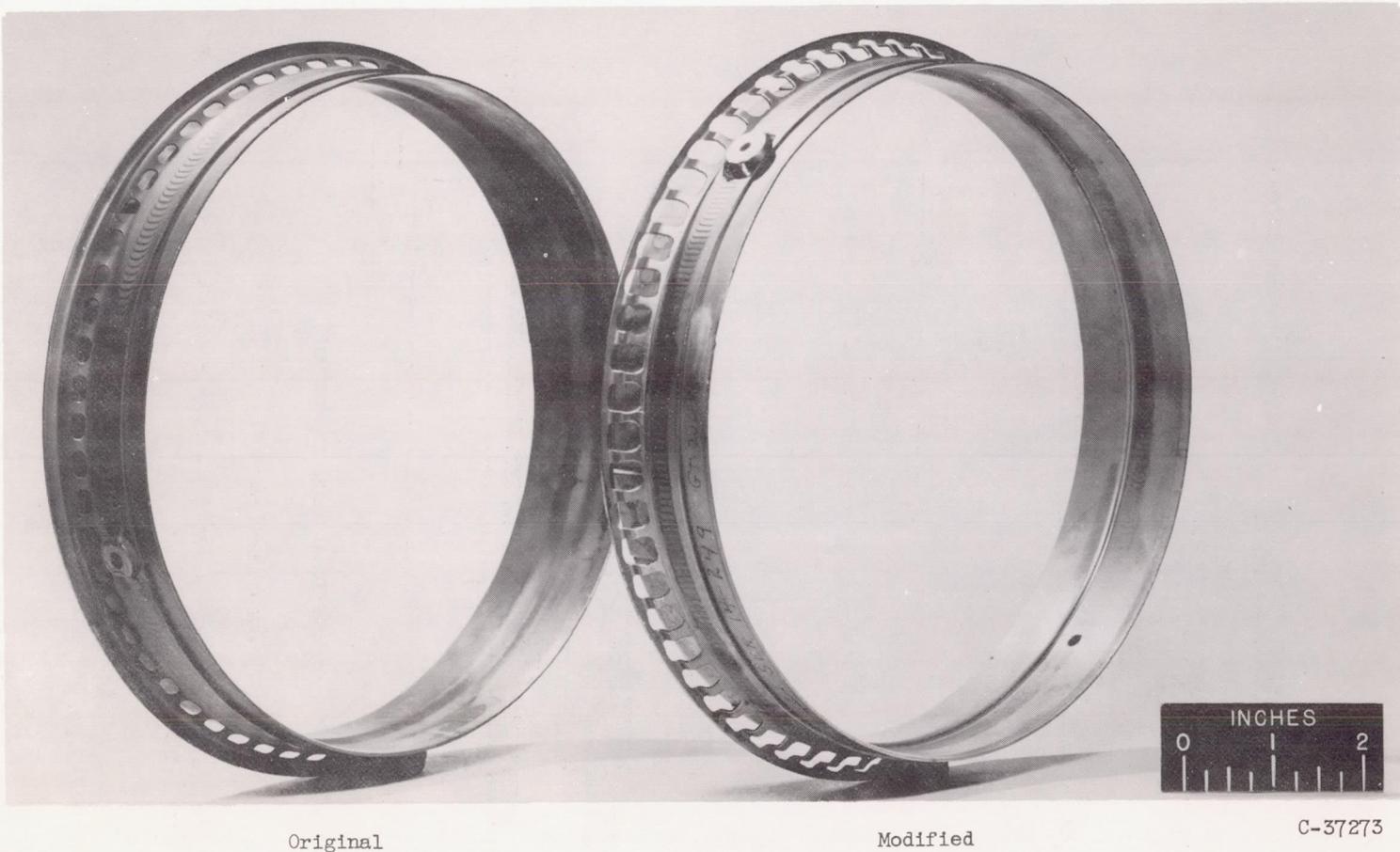
Original   Modified   C-37273

(b) Combustor-outlet retainer-ring modification.

Figure 2. - Concluded. Modifications to standard turbojet-engine components for operation with trimethyl borate fuel.

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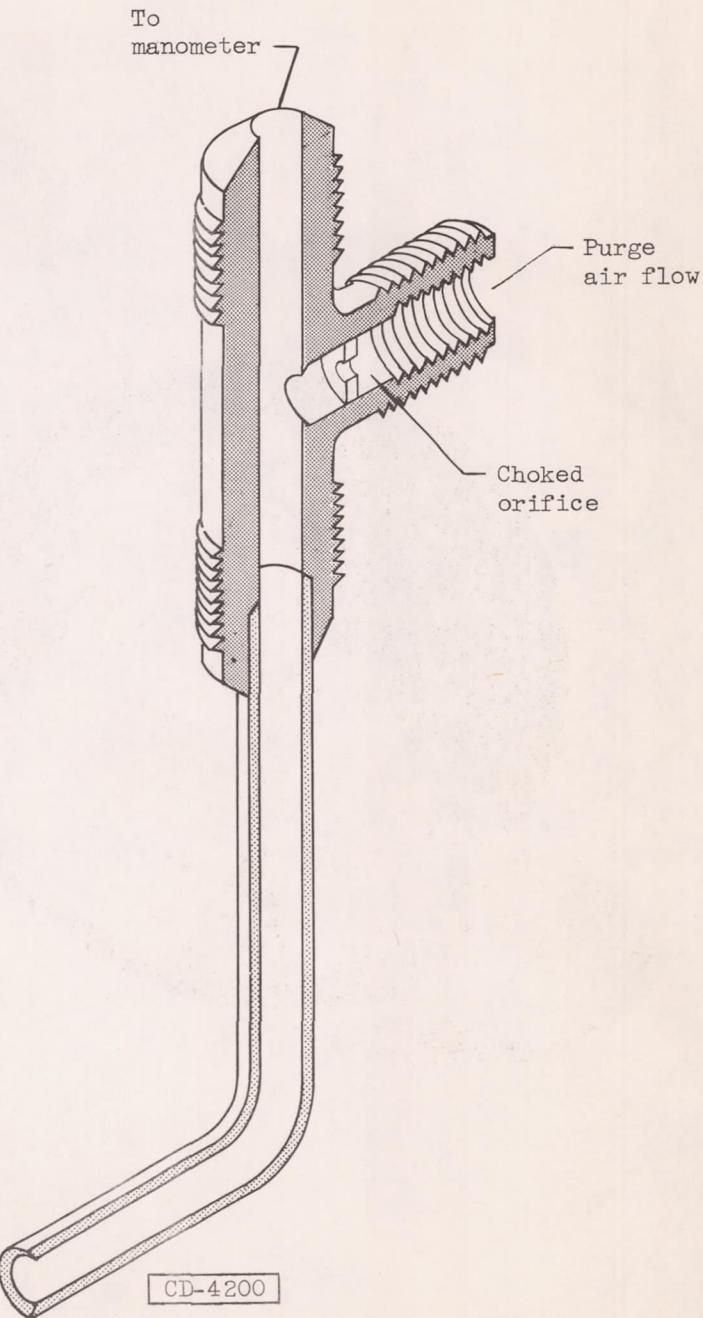
Figure 3. - Purge-type pressure instrumentation used downstream of combustor to prevent boric oxide interference.
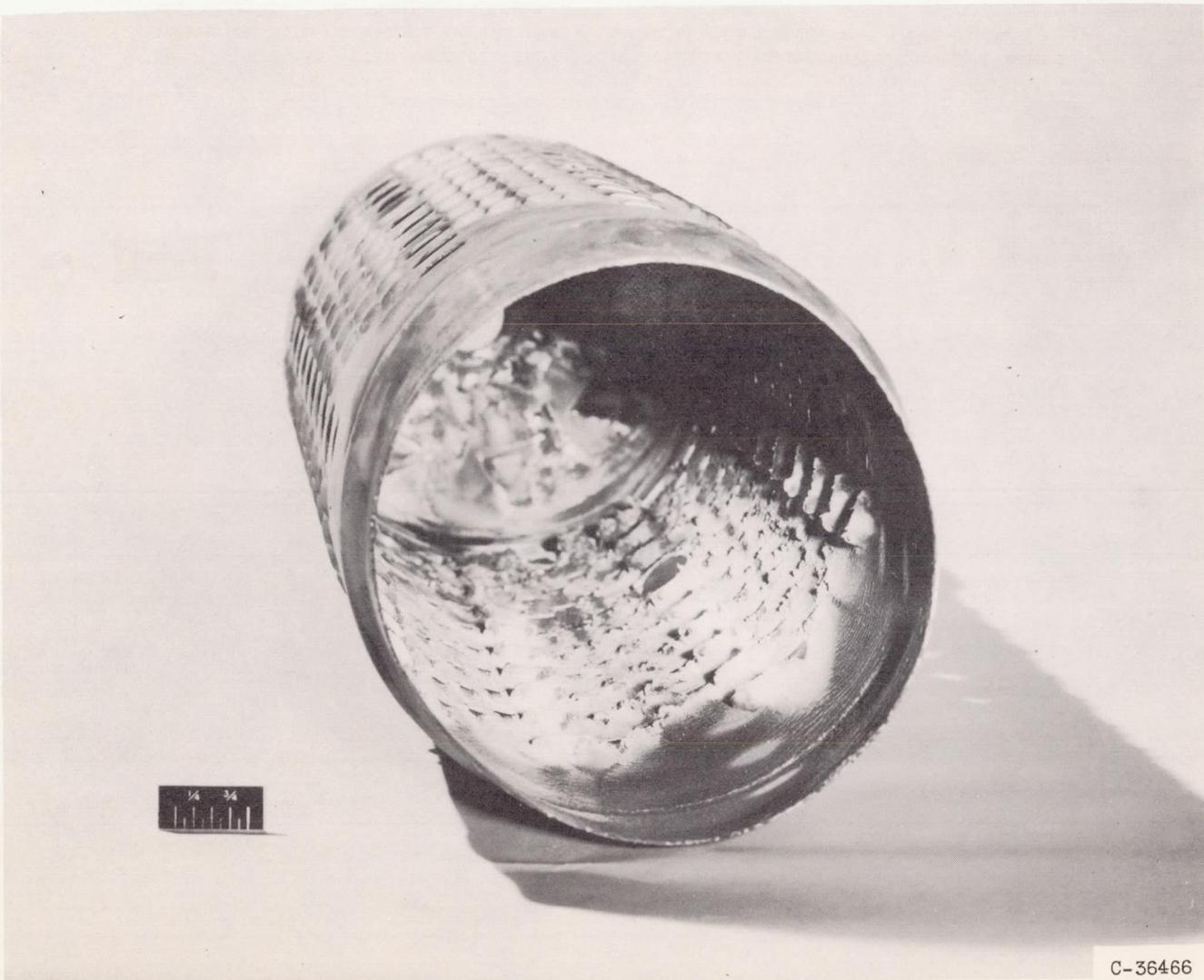
Figure 4. - Boric oxide deposits in combustion chamber following engine start and 7 minutes operation. Configuration A.

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C-36465

(a) Combustion chamber with thimbled liner.

Figure 5. - Boric oxide deposits in turbojet-engine components following 2 hours operation with trimethyl borate fuel. Rated engine conditions. Sea-level static operation. Configuration A.

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(b) Combustion chamber with thimbleless liner.

Figure 5. - Continued. Boric oxide deposits in turbojet-engine components following
2 hours operation with trimethyl borate fuel. Rated engine conditions. Sea-level
static operation. Configuration A.

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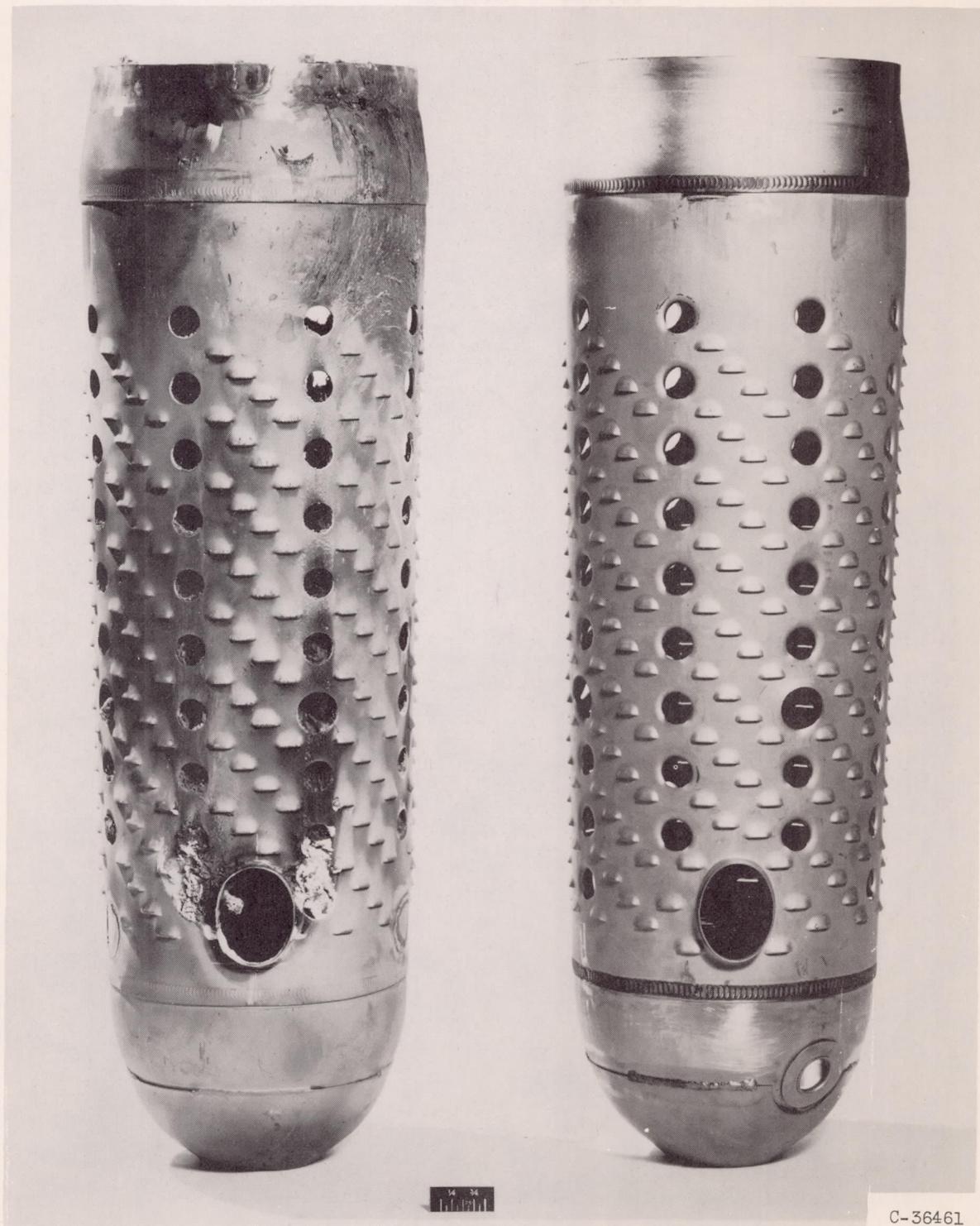
C-36461

(c) Longitudinal boric oxide deposition compared with clean combustion-chamber liner.

Figure 5. - Continued. Boric oxide deposits in turbojet-engine components following 2 hours operation with trimethyl borate fuel. Rated engine conditions. Sea-level static operation. Configuration A.

C-36395
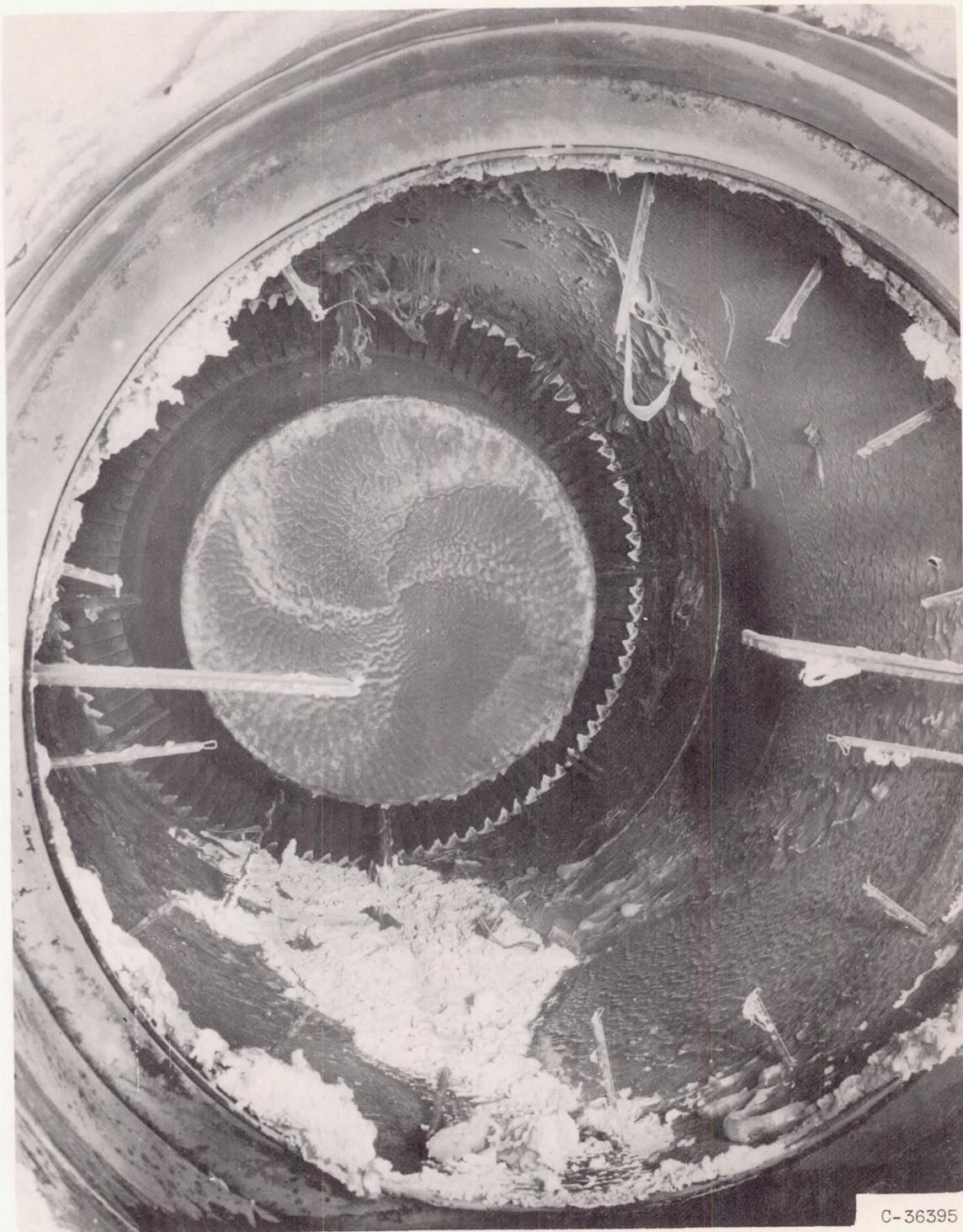
(d) Engine tail pipe, looking upstream.

Figure 5. - Concluded. Boric oxide deposits in turbojet-engine components following
2 hours operation with trimethyl borate fuel. Rated engine conditions. Sea-
level static operation. Configuration A.
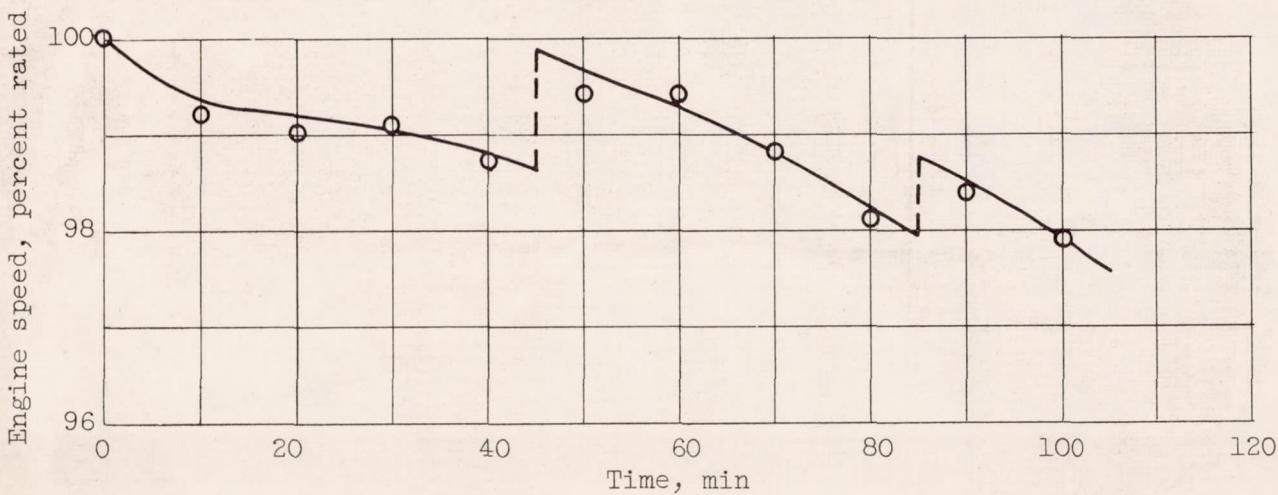
Figure 6. - Effect of boric oxide deposition on turbojet-engine speed. Configuration A. Tail-pipe temperature, 1700° R.

(a) Turbine-outlet and exhaust-gas temperatures.

(b) Combustor total-pressure ratio.
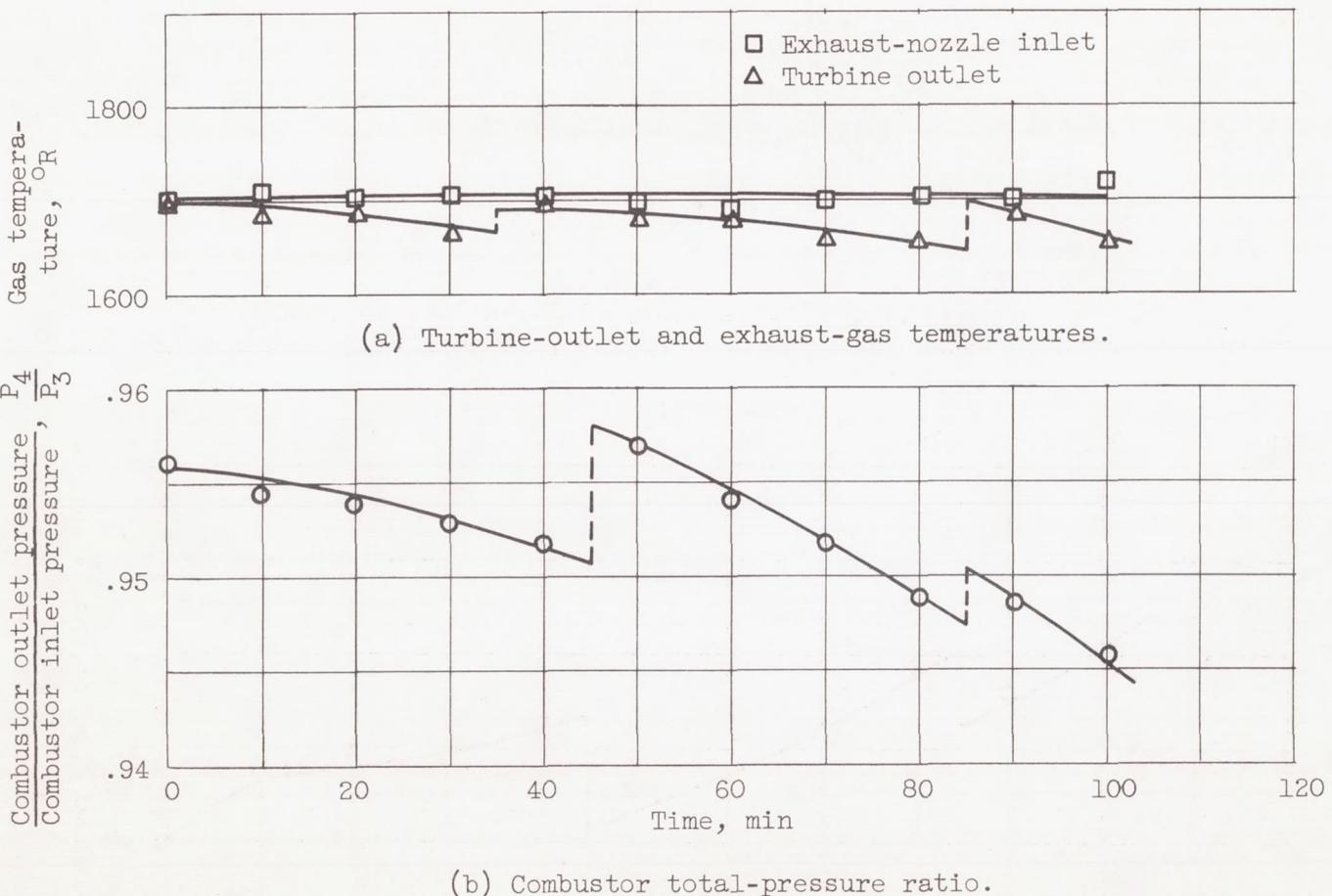
Figure 7. - Effect of boric oxide deposition on turbojet-engine tempera-
tures and pressures. Configuration A. Tail-pipe temperature, 1700° R.

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(a) Downstream of combustor 1.

(b) Between combustors 1 and 2.
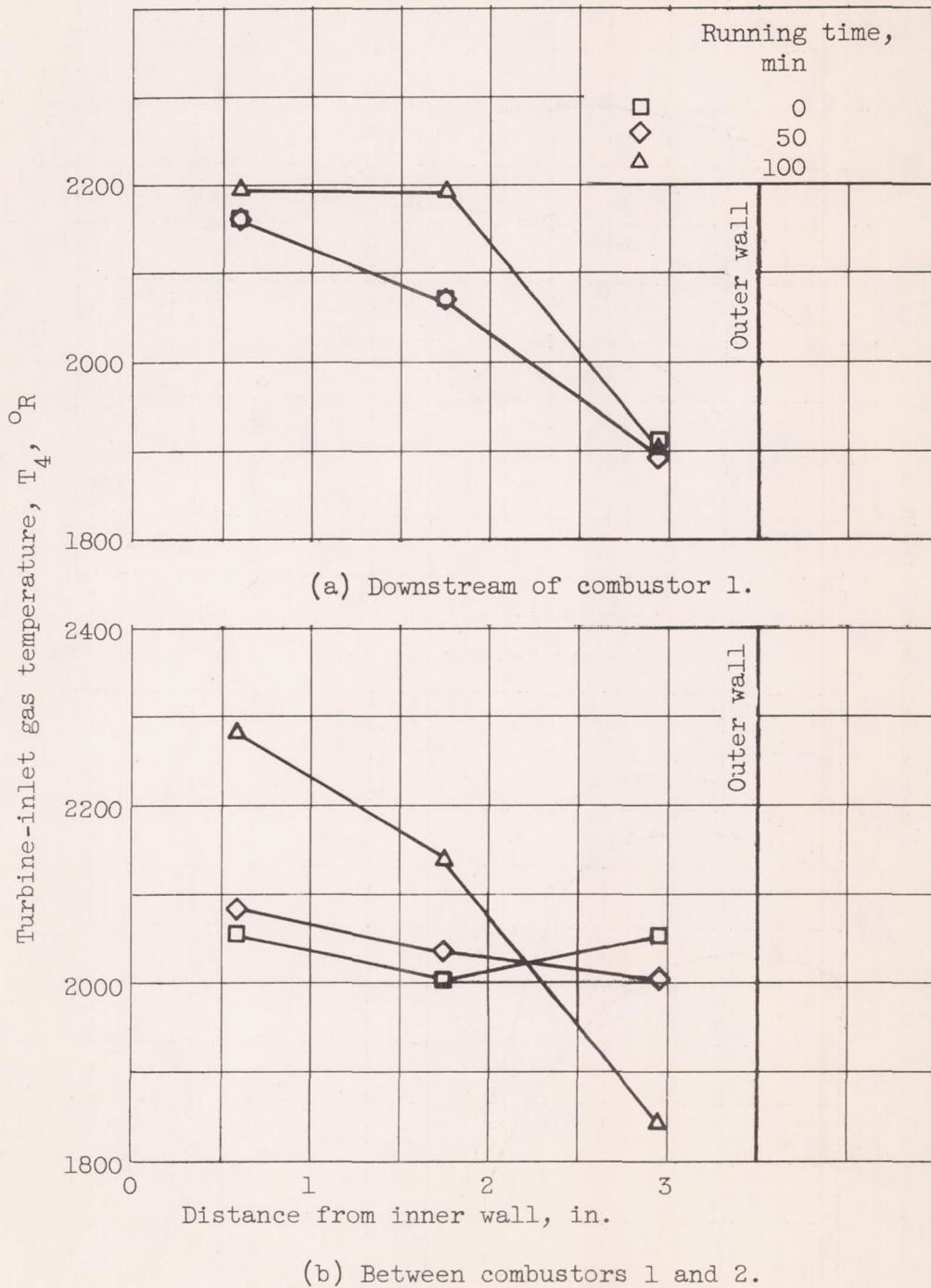
Figure 8. - Change in turbine-inlet gas-temperature profiles with operation of engine with trimethyl borate fuel.
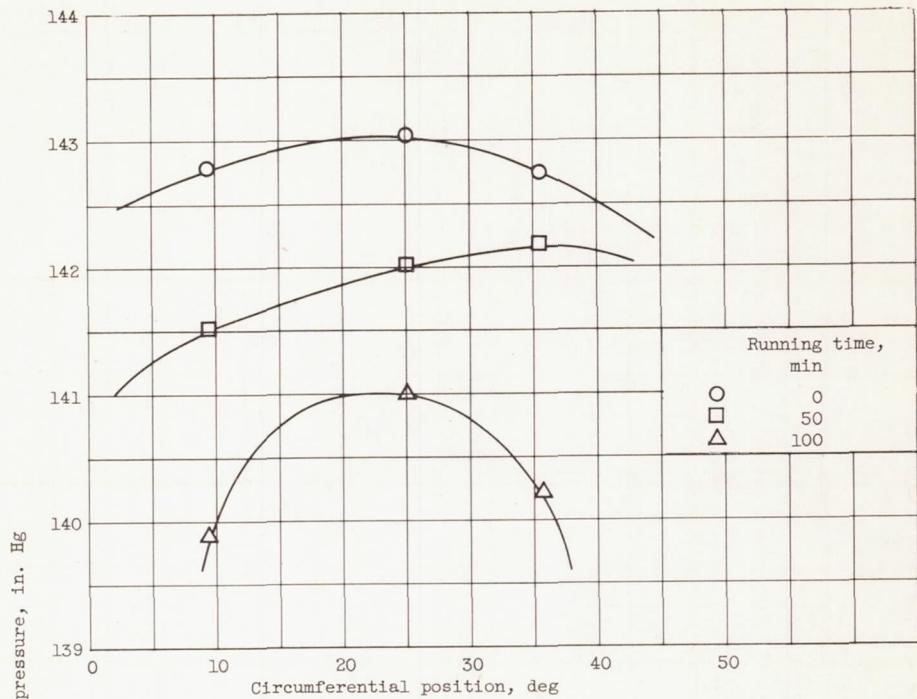
(a) Circumferential pressure distribution.
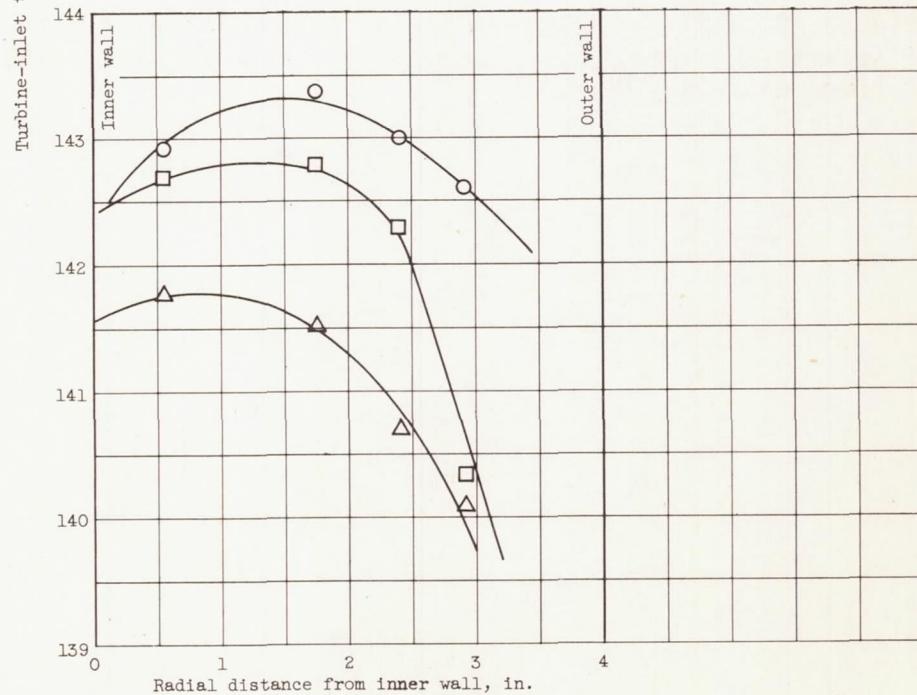
(b) Radial pressure profile.

Figure 9. - Change in turbine-inlet total-pressure profiles with operation of engine with trimethyl borate fuel.
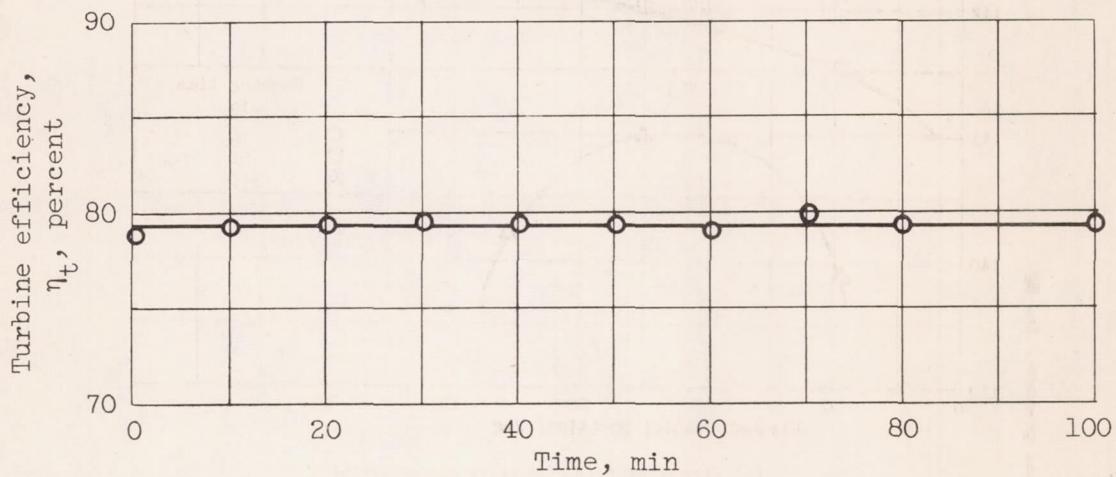
Figure 10. - Effect of operation of turbojet engine with trimethyl borate fuel on turbine efficiency. Tail-pipe temperature, 1700° R.
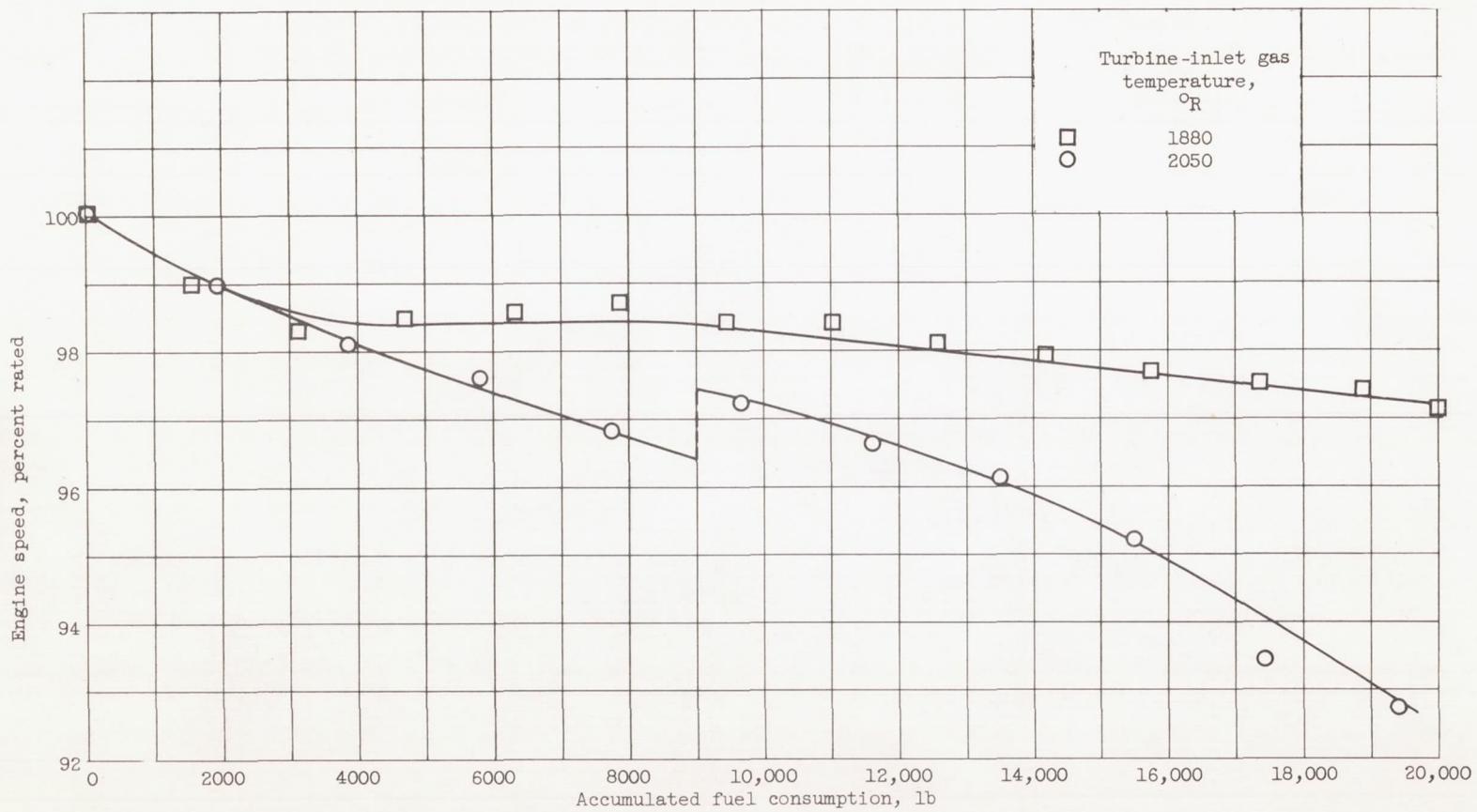
Figure 11. - Effect of turbine-inlet temperature on engine speed deterioration during operation with trimethyl borate fuel. Configuration B.
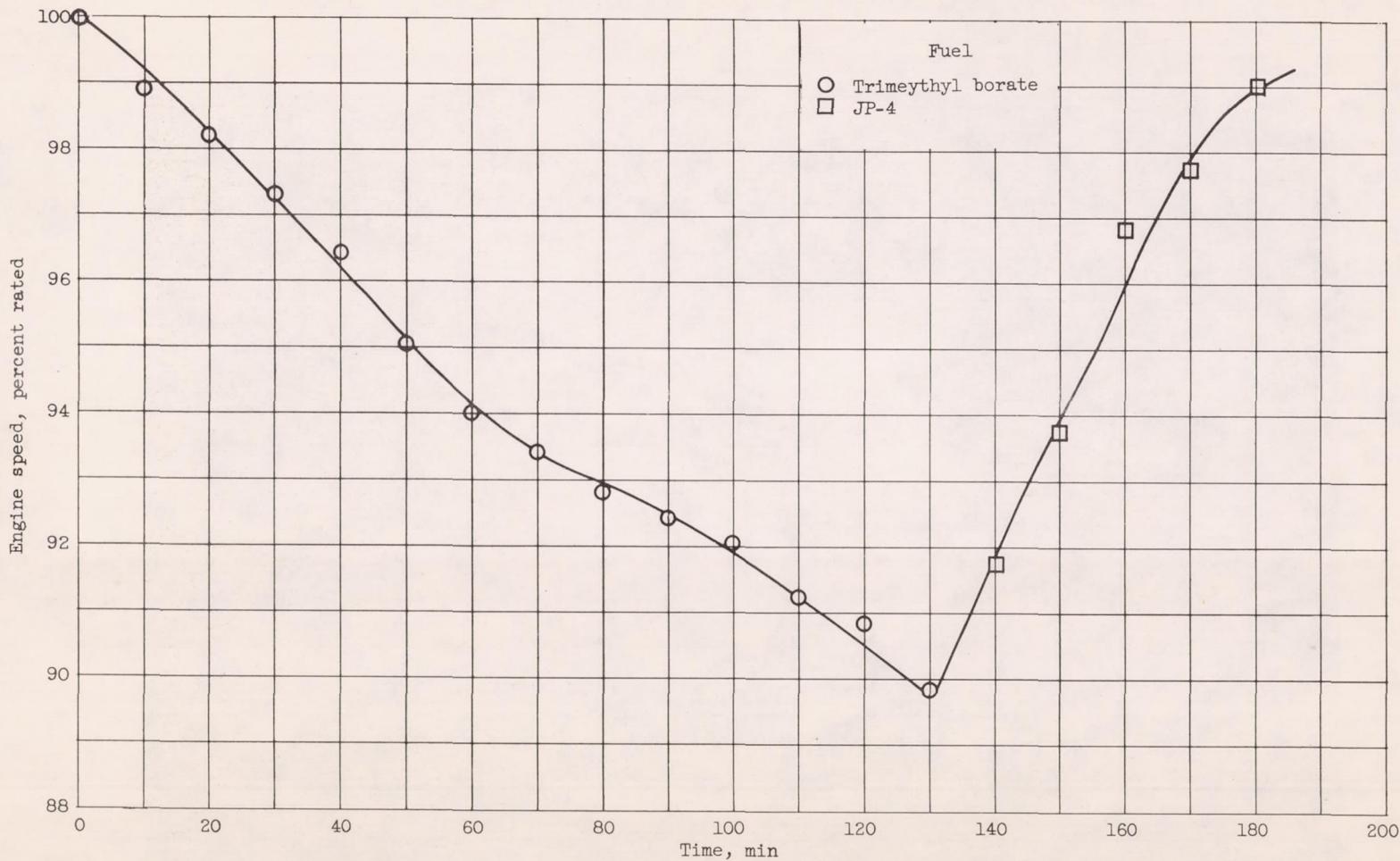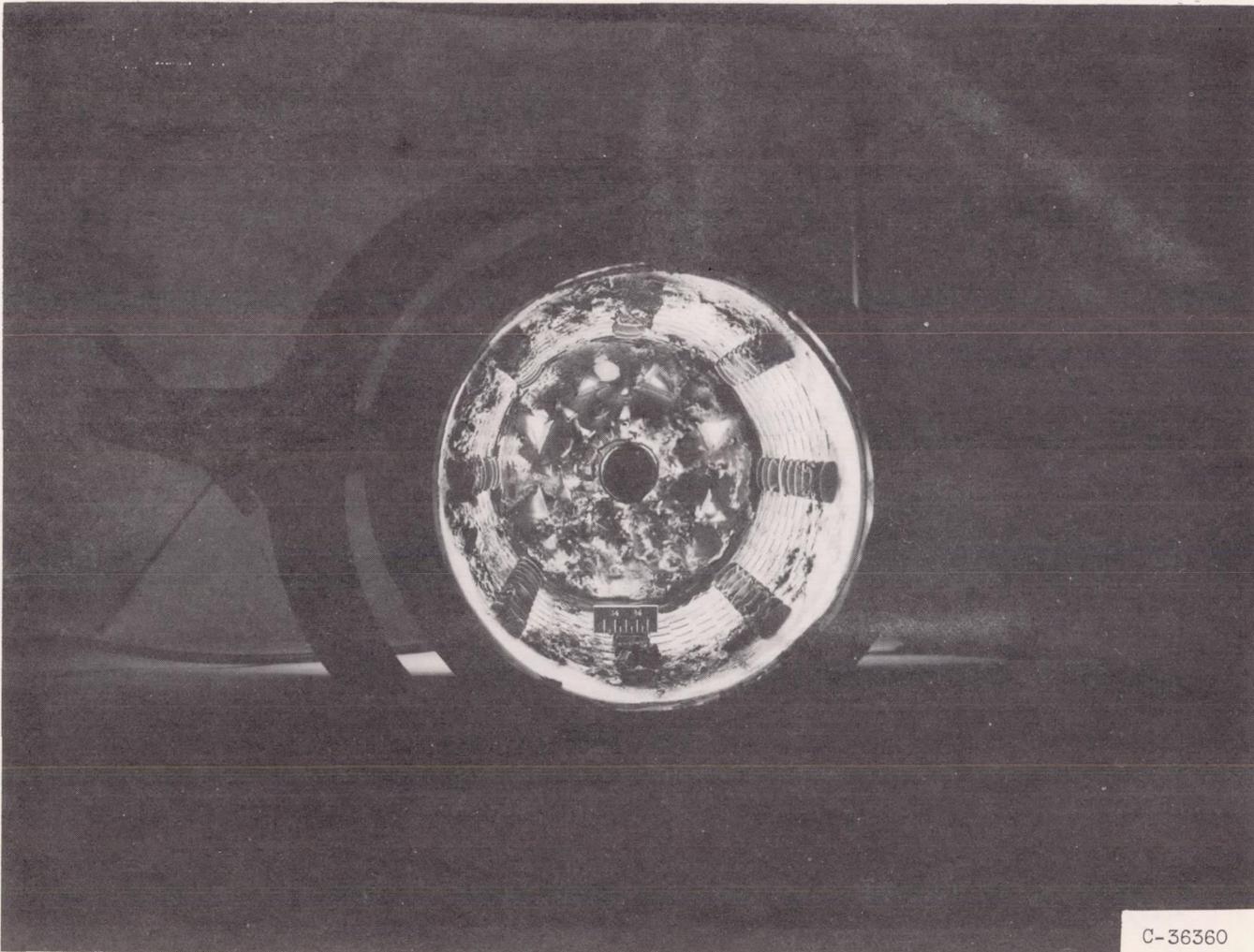
Figure 12. - Dissipation of effect of boric oxide deposits in engine components by operation with JP-4 fuel. Rated engine conditions. Static sea-level operation. Tail-pipe temperature, 1700° R. Configuration C.

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(a) Combustion chamber.

Figure 13. - Boric oxide deposits in engine components following operation with JP-4
fuel for 50 minutes. Previous trimethyl borate operation for 130 minutes. Con-
figuration C.
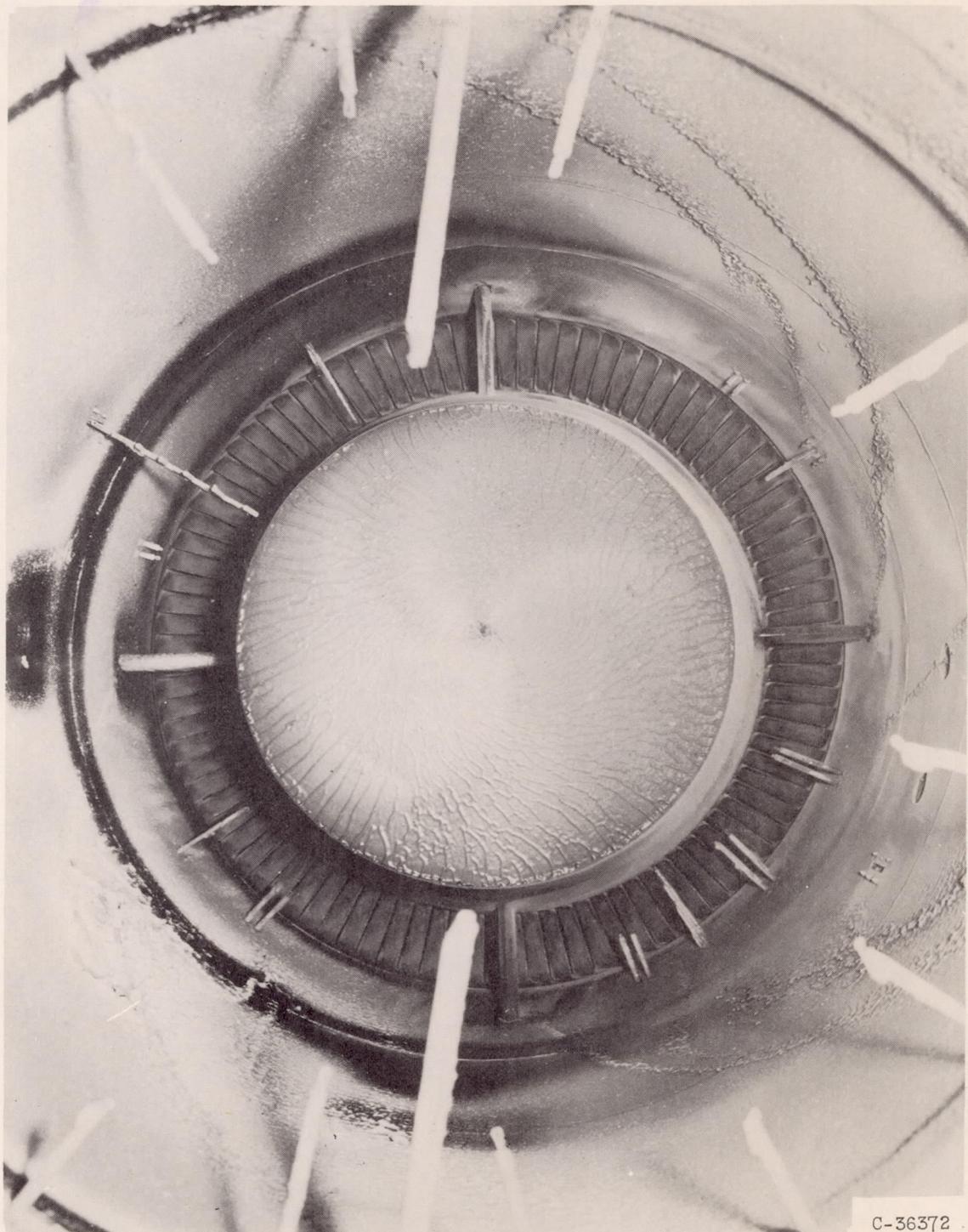
C-36372

(b) Engine tail pipe, looking upstream.

Figure 13. - Concluded. Boric oxide deposits in engine components following operation with JP-4 fuel for 50 minutes. Previous trimethyl borate operation for 130 minutes. Configuration C.